Optical Processes for the Generation of Microwave Signals

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Abstract - **Optical generation processes of micro-wave signals are presented along with their perspectives. The utilization of optical technology in microwave signal generation offers new features and improved performance: like wider tuning range, higher stability, lower noise, synchronization, etc. The optical signal generation has already many applications, and it is expanding rapidly.**

I. BEATING TWO LASER BEAMS

Microwave signal can be generated by beating two laser beams. Then a signal with the frequency difference between the two beams is obtained after optical detection:

$$I_{ph} \sim |\underline{E}|^2 \approx 2 \cdot \frac{q}{h \cdot c} \cdot \lambda_0 \cdot P_0 \cdot [1 + \cos(2\pi f_c \cdot t)] \qquad (1)$$

where

$$f_c \approx c \cdot \frac{\Delta\lambda}{\lambda_0^2} \qquad (2)$$

if $\Delta\lambda \ll \lambda_0$.

That type of signal generation provides an extremely wide tuning range which is only limited by the cut-off frequency of the photo-diode. The cut-off frequency of the photo-diode can be significantly increased by the application of a traveling wave type photo-diode. That is shown in Fig. 1.

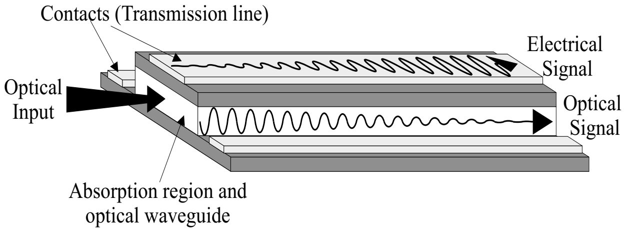

Fig. 1 Traveling wave photo-diode

The contact pads form a co-planar waveguide structure. The optical signal is guided along and leaked into the device. Photocurrent generated along the device is continuously added to the travelling electrical signal. The distributed nature of photo-absorption prevents current saturation.

In principle by beating two laser beams very high frequency can be generated, it can be even in the submillimeter wave region. In practice the generated frequency is limited by the responsivity of the photo-diode. The traveling wave photo-diode exhibits the highest responsivity in the submillimeter wave region, however, it is significantly decreased with increasing frequency according to the relationship f^{-4}.

That approach can be used to generate a signal swept over several octave band. For that purpose the wavelength of one of the lasers should be varied electronically.

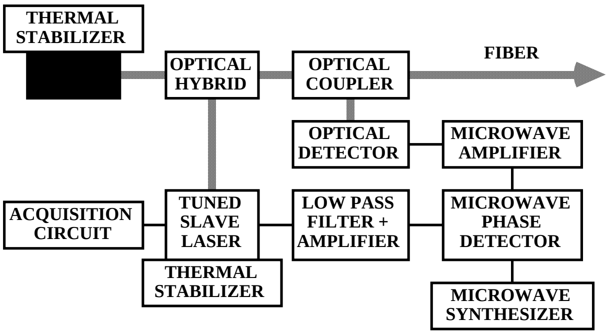

Fig. 2 Beating two laser beams

However, the generated microwave signal is not stable enough what is a significant problem in many applications. That problem can be overcome by a phase locked loop (PPL) keeping the difference frequency at a stable value. The phase looked loop is presented in Fig.2. There are two lasers one of them is called master laser and the other is called slave laser. The latter is tuned over a wide band. The output signals of the lasers are detected by a photo diode providing the difference frequency signal. This signal is compared with a reference signal and the error signal of the comparator is used to tune the slave laser. This way the stability of the difference frequency signal is ensured.

In that arrangement there are two bottle-necks: the cut-off frequency of the photo-diode and the frequency limitation of the reference signal. Nevertheless, that type of signal generation has several advantages. The generated signal can be varied in a very wide band (e.g. from 1 GHz to 100 GHz) which is very useful for wideband measurements. The difference signal can even be generated at a remotely located user because the two laser beams can be transported over a fiber to the user with small loss.

Further advantage is the modulation possibility of the generated signal. It is performed in the optical domain by a Mach Zehnder optical modulator. The modulator can produce intensity modulation on one of the beams. Usually digital modulation is applied.

II. MODE LOCKED LASER SOURCE

For the generation of microwave signals a mode locked laser source can also be used. In that case two modes of a laser are detected in a high speed photo-detector. The principle of this type of microwave signal generation is the same as in case of heterodyning the signals of two independent lasers. The generated signal is usually too noisy not only because of the laser RIN (relative intensity noise) but also due to the mode fluctuation noise. Therefore some kind of stabilization is needed.

According to the widely used approaches a clean and stable microwave signal is injected into the laser via its bias. Injection locking the laser by a signal with a frequency difference between the two modes will result in a clean and stable generated signal.

Different laser types can be used in the mode locked regime: e.g. semiconductor or solid state lasers. In case of a solid state microchip laser the frequency difference between the modes is determined by the length of the microchip crystal. As the temperature dependence of the crystal is much less than that of the semiconductors the frequency stability of the generated signal is much better compared to a semiconductor laser. In addition to that the noise is smaller because the solid state crystal has a high Q factor and thus it works as a filter. In that case the lasing operation is achieved by optical pumping.

The mode locked laser has regularly not only two modes which causes problems in the generation of a clean microwave signal. Therefore appropriate filtering is required. Increasing the microwave frequency is mainly limited by the responsivity of the photo-detector what is inversely proportional to f^4.

III. MODULATION OF THE LASER BEAM

Optical signal generation can be carried out in another way as well. That is shown in Fig. 3. Here only one laser is used and its beam is modulated by a microwave signal source.

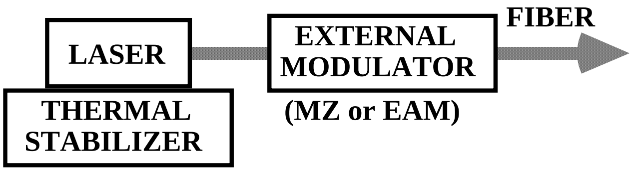

Fig. 3 Modulation of the laser beam

After photo-detection the microwave signal is regained to feed a remotely located user, e.g. the converters of a phased array antenna. That antenna has many radiating elements and the amplitude and phase of the feeding signal have to be controlled. This function can be performed easily in the optical domain. A distribution network is used to feed the antenna elements. The advantage of optical fibers used in the distribution network is that they are much lighter, more flexible, and free of electro-magnetic interference.

IV. OPTICAL TUNING OF MICROWAVE OSCILLATORS

The optical technology can be utilized for optical tuning of microwave oscillators in two different ways. According to the direct method the active element of the microwave oscillator is illuminated. Then by varying the light intensity the oscillator can be tuned. For that purpose two effects are utilized: the change in the capacitance of the active element and the excess gate-source current due to optical illumination. The change in the capacitance is relatively small, therefore the effect of the excess gate-source current is also utilized for increasing the tuning range.

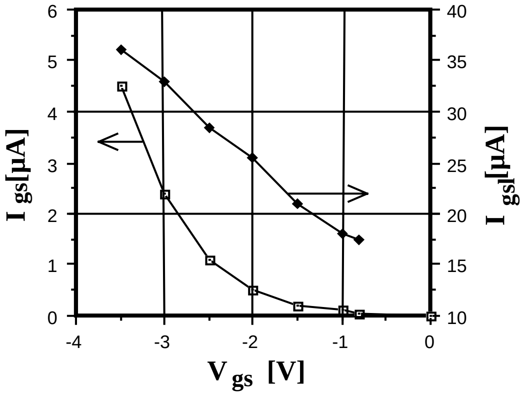

Fig. 4 Gate-source current with and without light illumination

Fig. 4 presents the excess gate-source current due to optical illumination. If that light induced current is flowing through an external resistance connected parallel to the gate-source capacitance the tuning band is highly increased.

That type of optical tuning results in a very wide tuning range as shown in Fig. 5. The maximum tuning range is about 10%. The optical tuning has the advantage of being free of electromagnetic interference.

In another approach the indirect illumination is applied. In that case the optical signal is detected by a photo-diode and the detected signal is utilized for tuning. Usually a varactor diode serves for that function and its capacitance is varied by the detected signal.

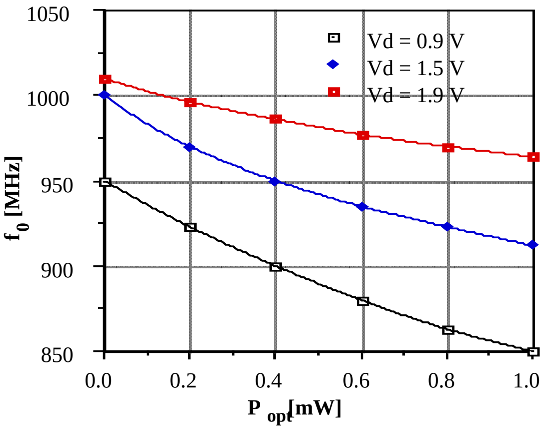

Fig. 5 Optical tuning of a microwave oscillator. The parameter of the curves is the drain-source voltage

V. OPTICAL CONTROL OF MICROWAVE PHASE LOCKED OSCILLATORS

The optical control of microwave phase locked (PLL) oscillators is well applicable for improving its frequency stability and noise performance. The block diagram of an optically controlled PLL oscillator is shown in Fig. 6.

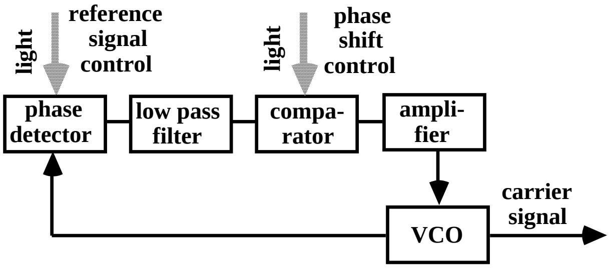

Fig. 6 Optical control of a PLL oscillator

The intensity of the lightwave is modulated by a reference microwave signal. The devices in the phase detector are illuminated by the modulated light thus delivering the reference signal for phase detection. The phase locked loop serves for stabilizing the oscillation frequency. The low-pass filter in the loop has a low cut-off frequency preventing the oscillator from the higher frequency noise components of the relative intensity noise (RIN) of the laser.

VI. OPTICAL INJECTION LOCKING OF A MICROWAVE OSCILLATOR

There are two main requirements for microwave oscillators: to generate signals with low noise and high frequency stability. Both requirements can be met by injecting a clean signal into the oscillator. That method is called injection locking. The optical injection locking of microwave oscillators is a good method to reduce the oscillator noise and to increase its frequency stability. This way several oscillators can be controlled using a central reference signal which is optically distributed to the local oscillators. Then the oscillator signals are coherent what is important e.g. in cellular mobile networks or in phased array antennas.

The optical injection locking can be performed in a direct or indirect way. In the direct way the active element of the oscillator is illuminated by an optical signal carrying a clean microwave signal. When the free running oscillation frequency is close to the injected signal frequency the locking process is effective. That means the oscillator output signal frequency will be the same as the frequency of the optically injected microwave signal and the noise will also be reduced close to the noise of the injected signal.

The main problem in the direct method is that the coupling between the optical signal and the oscillator signal is not strong enough and so the locking band is small. Therefore the temperature dependence of the oscillator has to be also very small.

In the indirect injection locking techniques the optical signal carrying the clean microwave signal is first detected and then the generated microwave signal is used for injection locking. Applying that method the locking band will be wider due to stronger coupling. In spite of that advantage it is preferable to apply simultaneously a phase locked loop to keep the self-oscillation frequency at the frequency of the injected signal.

That double locking method is shown in Fig. 7. The clean signal is used partly as a reference signal for the phase locking loop adjusting the free running oscillation frequency to be equal to the frequency of the clean signal. The other part of the clean signal is injected into the oscillator to reduce its noise.

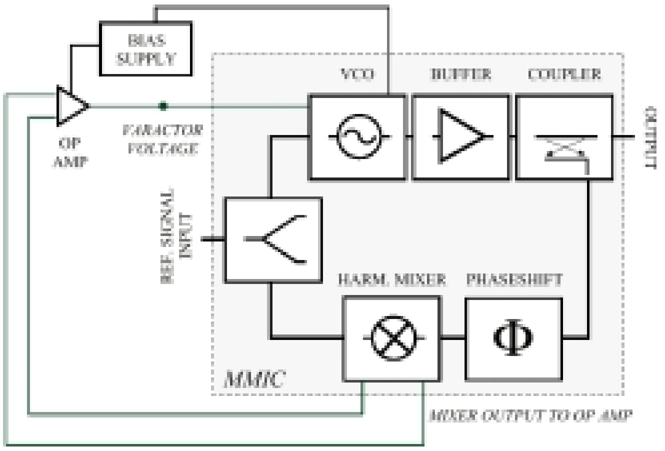

Fig. 7 Block diagram of the double locking method

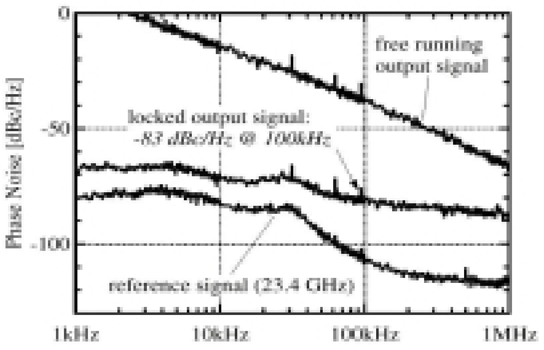

Fig. 8 Phase noise of a 94 GHz MMIC oscillator optically injection and phase locked at the 4th subharmonic

That method was used to stabilize an MMIC 94 GHz millimeter wave oscillator. The clean signal was transported via a fiber utilizing an optical carrier. After optical detection its frequency was multiplied and then it was used for subharmonic injection and phase locking of the oscillator. The noise spectrum of that oscillator is presented in Fig. 8.

VII. OPTO-ELECTRONIC OSCILLATOR

The optical technology offers a new method for constructing extremely low noise microwave oscillators. The reason is that utilizing an optical cavity as a microwave resonator an extremely high Q factor can be achieved. For that purpose a long fiber with high reflectances on its both ends is the best approach. The Q factor of that resonator is:

$$Q = \pi k \frac{\exp(-\alpha_r d/2)}{1 - \exp(-\alpha_r d)} \qquad (3)$$

where

$$\alpha_r = \alpha_f + \frac{1}{2d} \ln\,[1/(R_1 R_2)] \qquad (4)$$

Here α_f is the intensity attenuation factor of the fiber, R_1 and R_2 are the reflectances at the ends of the fiber, d is the length of the fiber and k is the number of half wavelengths along the fiber:

$$k = 2d/\lambda \tag{5}$$

assuming k is an integer number.

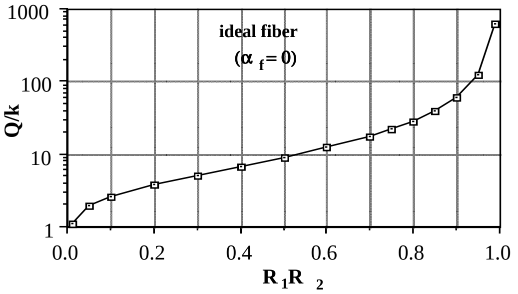

Fig. 9 Q/k as a function of fiber reflectances

The dependence of the Q factor on the different parameters is presented first in Figs. 9. and 10. These figures show the Q/k value as functions of the intensity attenuation factor of the fiber: α_f and the reflectances at the fiber ends R_1R_2.

In Fig. 9 the Q/k value is plotted versus R_1R_2 assuming a fiber with zero attenuation. As seen Q/k is strongly dependent on the reflectances. High Q/k is only obtained if the reflectances are very close to unity. The reflectances are determined by the mirrors at the fiber ends and by the coupling in and out of the fiber resonator. Therefore only loose coupling can be used. By other words the loaded Q factor should be close to the unloaded Q factor.

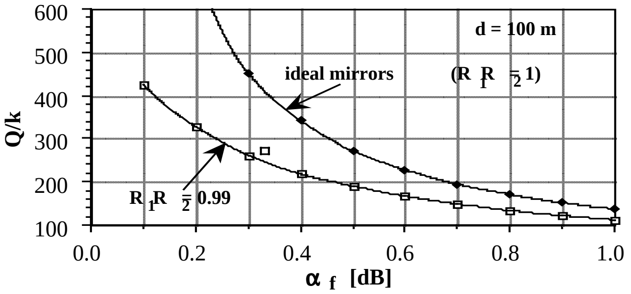

Fig. 10 The Q/k value as a function of the fiber intensity attenuation factor

In Fig. 10 the Q/k value is plotted as a function of the fiber intensity attenuation factor, α_f for two different reflectances at the fiber ends: in case of the upper curve $R_1R_2 = 1$ and in case of the lower curve $R_1R_2 = 0.99$. The first case represents the so called ideal case which means total reflections at the fiber ends. As seen the reflectances have a very significant effect, much higher than the fiber intensity attenuation factor.

Based on Eq. (5) increasing the length of the fiber, k the number of the half wavelengths along the fiber will also be increased resulting in a proportional increase in the Q factor. This way an extraordinary enhancement of the Q factor is achieved. However, the number of resonances will also be increased and that makes the separation of the resonances more difficult.

The frequency difference between the neighboring resonances is:

$$\Delta f = c/(2d\sqrt{\varepsilon_f}) \tag{6}$$

where c is the velocity of light and Δf is the effective dielectric constant (or permittivity) of the fiber.

The application of the fiber resonator in the optical generation of microwave signals is presented in Fig. 11. Here the beam of a laser is modulated by a Mach Zehnder optical modulator. By applying a microwave bandpass filter and proper feedback microwave oscillation is generated. The performance can be significantly improved by applying a fiber resonator in the feedback loop. The high Q factor of the fiber resonator stabilizes the generated frequency. With proper design the phase noise can be reduced to an extremely low level. The generated microwave signal can be obtained either in the electrical domain or in the optical domain.

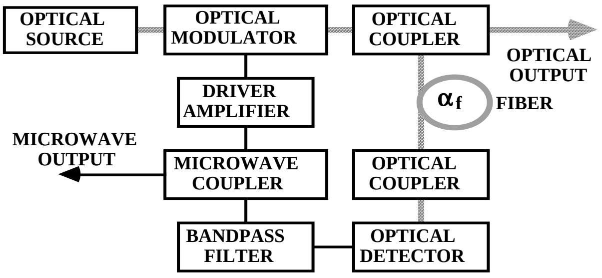

Fig. 11 Opto-electronic oscillator block diagram

The main problem of that type of opto-electronic oscillator is how high reflectances can be achieved at the ends of the fiber resonator considering the input and output coupling to it as well. The other problem is the separation of the resonant frequencies because they are relatively close to each other when the length of the fiber is increased. A further problem is the temperature dependence of the fiber what is the frequency determining element. The fiber resonator has many resonances and a small change in its length can cause a significant frequency shift. Temperature stabilization and control of the oscillation frequency are needed for stable operation.

VIII. CONCLUSIONS

In this paper the different methods for optical generation of microwave signals have been presented along with their perspectives.

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